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Test of cables made of 1-mm OST-MJR strand at BNL

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Abstract:

This report shows the results and analysis of the test of FNAL-C1-MJR-1. This was a sample consisting of two “cos-theta cables” (i.e. keystoned cables with 28 strands of 1-mm diameter) made of MJR strands produced by Oxford Superconducting Technology. It was tested at BNL in background field from 0 to 7 tesla at varying ramp rates from 150 to 990 A/s. Most of the quenches occurred at a current between 14.5 and 15.5 kA at any background field. The quench-start location moved from one sample to the other and within each sample. Each cable was instrumented with a pair of voltage taps in the field region (covering about half the field region) and voltage taps outside the splices. Three fast acquisition channels were used during tests in order to check if the quench started inside a pair of voltage taps. The data analysis showed quenches starting inside the voltage tap pairs at 0 tesla. On the contrary, no quench started inside the voltage tap pairs at 7 tesla.

1.0 Sample description

The sample consisted of two "cos-theta" Nb_3Sn cables, 1220 mm long. The cable parameters are shown in Table 1. The strand was produced by Oxford Superconducting Technology (OST) using the MJR method. The cables were insulated using ceramic tape and ceramic binder as in FNAL Cos-theta short model magnets. The heat treatment was performed following the instructions provided by the vendor as for the short model magnets. The sample holder used for the test is shown in Fig. 1. It was previously used both at BNL and at NHMFL for testing ITER cables for developing the React-and-Wind technology. A description of the sample holder and of the test results may be found in [1-3]. The sample holder was designed for Nb_3Sn cables with 41 strands having 0.7 mm diameter. A few parts were modified in order to accommodate cos-theta cables (thicker and slightly less wide than those previously tested). A moderate pre-stress of about 12 MPa was applied after impregnation [4].

Number of strands	28
Strand diameter (mm)	1.000
Cable width (mm)	14.232
Cable thickness – major edge (mm)	1.913
Cable thickness – minor edge (mm)	1.687
Transposition pitch (mm)	110

TABLE 1: Cable parameters and nominal dimension before heat treatment.

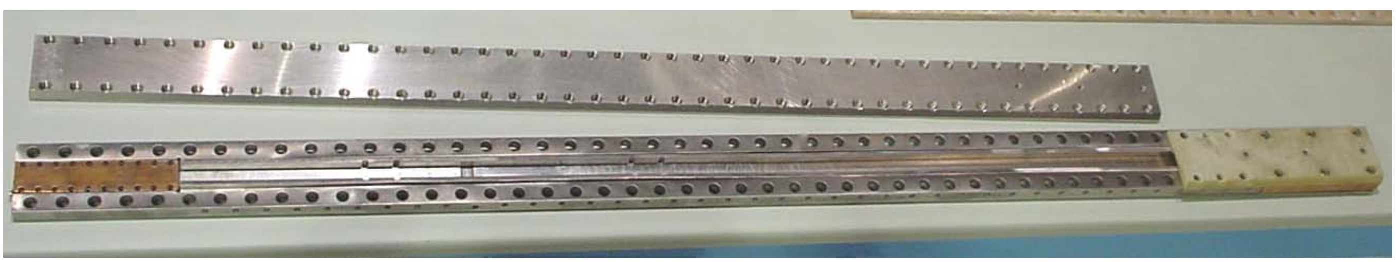

Figure 1: Parts of the cable sample holder

2.0 Test facility

The sample was tested at BNL Cable Test Facility. Its main features are:
- Max field: 7 T @ 4.2 K
- Length of uniform field region: 600 mm
- Max current: ~25 kA (Max current for leads is 20 kA in steady state)
- Magnet ramp-up time: 15 minutes

The sample was installed in the test facility in such a way to be centered longitudinally with respect to the background field (i.e. center of the field = center of the sample) and to have the background field anti-parallel to the sample self field. A FE analysis [3] showed that in this configuration the sample is under a moderate compression at 7 T and maximum current (25 kA).

The test was performed at 4.43 – 4.45 K.
Ramp rates varied from 150 to 990 A/s. Table 2 reports the quench current, the background field and the ramp rate of all quenches (BNL cable test run 4391).

3.0 Instrumentation and data acquisition

Each cable was instrumented with a pair of voltage taps in the field region (covering about half the field region) and voltage taps outside the splices. The voltage taps inside the sample holder were soldered on the edge of the cable, in order to minimize the risk of stress concentrations during application of the pre-stress or under the magnetic forces. A multi-channel acquisition system and two oscilloscopes were used during test. The oscilloscopes could read two channels each and were not synchronized. Different set-ups were used during the first quenches in order to find the best configuration. We saw that the multi-channel system was too slow to detect the quench origin and only the oscilloscopes were used for quench #7 and following. The list of all the signals recorded during the quenches is shown in Table 3. Columns 5 and 7 show the signals recorded by the first oscilloscope, columns 9 and 11 by the second one. Figure 2 shows the position of the voltage taps on the samples. The most used configuration was the following: each oscilloscope was set to read the signal of the voltage taps in the field region of a cable (NM or BC) and the signal of the whole sample (AL). The AL signal was used to synchronize the oscilloscopes and the other signals (NM and BC) were compared with the AL signal in order to check if the quench started inside a pair of voltage taps (see examples in Figures 6 to 8).

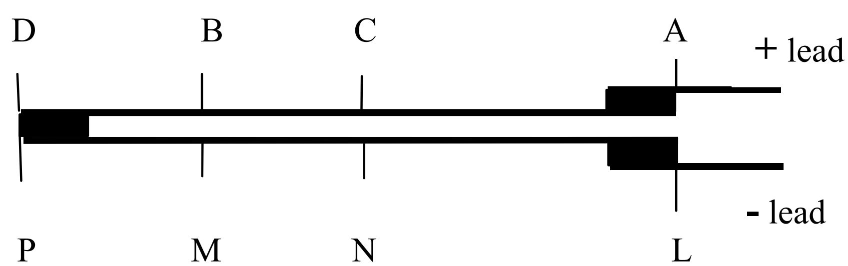

Figure 2: Voltage taps schematic

4.0 Results

The list of all quenches is reported in Table 2. Figure 3 shows the quench history high lightening the background field and the ramp rate of each quench. Figures 4 and 5 show the quench current versus the background field and the ramp rate dependence at 7 T.
The analysis of all the quenches whose recorded data could be synchronized (i.e. quench #10, 12, 13, 14, 15, 41, 43, 44, 45, 46, 48 and 49) gave the following results:

- **Without background field:** <u>Two quenches (#43 and #45) out of 7 started within the voltage tap pair on cable 1 (BC)</u>. When the quench didn't start from BC, the time delay for the propagation within the first voltage tap pair was in the range from 2 to 12 ms. Only in quench #44 the quench propagated first into NM and then into BC.

- **In 7 T background field:** None of the 5 quenches started within any voltage tap pair. The time delay for quench propagation within the first voltage tap pair was in the range from 1 to 4 ms.

Figures 6 and 7 show the voltage growth at the beginning of quenches #43 and #45 respectively. Figure 8 shows the voltage growth at the beginning of quench #10 that is the one with the shortest time delay before the quench propagation within any voltage tap pair, among the quenches in 7 T background field.

A similar behavior (i.e. quenches without field and no quenches under field at the same current) was seen in a piece of cable of HFDA03 cos-theta coil [5].

Looking at the quench history plot (Figure 3) it could be noted that the first quench after a reduction of the background field (i.e. from 7 to 3, from 3 to 1 and from 1 to 0 tesla) occurred at a current significantly lower than the current of all other quenches at the same field.

5.0 Conclusions

The quench history shows that the background field (in the range from 0 to 7 tesla) did not affect the quench current. This behavior could not be explained by damage in one or more parts of the samples outside the field region due to the following factors:

- The fluctuation of the quench current by more than 1000 A.
- The quench location wasn't the same in all quenches: sometimes it was within a voltage tap pair (BC), sometimes close to a pair (more often BC, one time NM) and sometimes far from both voltage taps.
- Some quenches started within a voltage tap pair when the background field was off. If this was the sign of degradation, than that cable should have not reached the same current in 7 tesla background field.

Other possible explanations of this peculiar quench history could be based on mechanical issues like conductor movements, epoxy cracks or others. The previously listed objections are valid also in this case and it's very difficult to think about a combination of mechanical problems that could give the same quench current with and without background field and explain all the results here reported.

A possible adequate explanation of all these results is based on the assumption that the strands used to make these cables are unstable at low fields [6, 7]. Under this assumption these cables may quench at lower current without background field (i.e. subject to the self-field only) than in a moderate field (7 tesla). Since the cables tested extended outside of the background field, the quench current is not expected to change in function of the field, but the quench location should (i.e. no quench should start from the cable sections in background field). Therefore this assumption could explain why some quenches occurred within the voltage taps (BC) when the background field was off and didn't when the background field was on. It may also explain the scattering of the quench current because this is a typical behavior of unstable conductors.

References

1) P. Bauer, K. Ewald, J. Ozelis *"Design of a Sample Holder for Measurement of Nb_3Sn Cable Critical Current Under Transverse Loading Conditions"*, Fermilab Technical Division note TD-99-051*.
2) P. Bauer, et al. *"Fabrication and Testing of Rutherford-type Cables for React and Wind Accelerator Magnets",* IEEE Transactions on Applied Superconductivity, vol. 11, no. 1, pp. 2457-2460, (2001).
3) P. Bauer, et al., *"Results of the Third Series of Measurements of the Critical Currents of Nb_3Sn Cables for the React & Wind Cable Development Program"*, Fermilab Technical Division note TD-01-069*.
4) G. Ambrosio *"2D Magnetic and Mechanical Analysis of the Sample Holder for Cable Test at BNL"*, Fermilab Technical Division note TD-04-001*.
5) S. Feher et al., "Test Results of Shell-type Nb3Sn Dipole Coils", to be published in MT-18 Proceedings, Morioka Japan (2003).
6) V.V. Kashikhin, A.V. Zlobin *"Magnetic instabilities in Nb_3Sn strands"*, Fermilab Technical Division note TD-03-032*
7) E. Barzi private communication.

* Available on line at: http://www-td.fnal.gov/info/td_library.html

Quench #	Current *A*	Field *T*	Ramp *A/s*
1	14610	0	manual
2	15111	0	150
3	14880	0	150
4	14952	0	150
5	15387	0	150
6	14799	0	150
7	14550	0	150
8	14283	0	150
9	14964	0	150
10	14826	7	150
11	14976	7	150
12	15837	7	150
13	14988	7	150
14	15156	7	150
15	15483	7	300
16	15309	7	300
17	15309	7	300
18	14751	7	300
19	14565	7	300
20	14748	7	990
21	16005	7	990
22	15084	7	990
23	16050	7	990
24	16050	7	990
25	15900	7	600
26	15900	7	600
27	15666	7	600
28	14511	3	150
29	15321	3	150
30	15810	3	150
31	15027	3	150
32	13680	1	150
33	14625	1	150
34	15327	1	150
35	15717	1	150
36	14628	1	150
37	13083	0	150
38	14712	0	150
39	14721	0	150
40	14967	0	150
41	14787	0	150
42	14982	0	150
43	14631	0	300
44	14949	0	300
45	14580	0	990
46	15354	0	990
47	15360	0	990

48	14862	0	990
49	14769	0	600
50	14040	0	600
51	15231	0	600
52	14730	0	150

TABLE 2: Quench current (A), background field (T) and ramp rate (A/s) of all quenches performed during the test.

Quench #	*Field* T	*Ramp rate* A/s	*Iq* A	*V1* V	*Gain_1*	*V2* V	*Gain_2*	*V3* V	*Gain_3*	*V4* V	*Gain_4*
1	0.0	manual	14610	Current	3000	BC	10	AD	1		1
2	0.0	150	15111	Current	3001	BC	10	AL	1	AM	1
6	0.0	150	14799	BC	1	NM	1				
7	0.0	150	14550	NM	10	LP	1	BC	10	AD	1
8	0.0	150	14283	NM	10	LP	1	BC	10	AD	1
9	0.0	150	14964	NM	10	LP	1	BC	10	AD	1
10	7.0	150	14826	NM	10	AL	1	BC	10	AL	1
12	7.0	150	15837	NM	10	AL	1	BC	10	AL	1
13	7.0	150	14988	NM	10	AL	1	BC	10	AL	1
14	7.0	150	15156	NM	10	AL	1	BC	10	AL	1
15	7.0	300	15483	NM	1	AL	1	BC	10	AL	1
16	7.0	300	15309	LM	1	AL	1	AB	10	AL	1
19	7.0	300	14565					AB	1	AL	1
20	7.0	990	14748	LM	10	AL	1	BC	10	AL	1
28	3.0	150	14511	LM	10	AL	1	BC	10	AL	1
29	3.0	150	15321	LM	10	AL	1	BC	10	AL	1
30	3.0	150	15810	LM	10	AL	1	BC	10	AL	1
31	3.0	150	15027	LM	10	AL	1	BC	10	AL	1
33	1.0	150	14625	LM	10	AL	1	BC	10	AL	1
34	1.0	150	15327	LM	10	AL	1	BC	10	AL	1
35	1.0	150	15717	LM	10	AL	1	BC	10	AL	1
37	0.0	150	13083	LM	10	AL	1	BC	10	AL	1
38	0.0	150	14721	LM	10	AL	1	BC	10	AL	1
40	0.0	150	14967	LM	1	AL	1	BC	10	AL	1
41	0.0	150	14787	NM	1	AL	1	BC	10	AL	1
43	0.0	300	14631	NM	1	AL	1	BC	10	AL	1
44	0.0	300	14949	NM	1	AL	1	BC	10	AL	1
45	0.0	990	14580	NM	1	AL	1	BC	10	AL	1
46	0.0	990	15354	NM	1	AL	1	BC	10	AL	1
48	0.0	990	14862	NM	10	AL	1	BC	10	AL	1
49	0.0	600	14769	NM	10	AL	1	BC	10	AL	1

TABLE 3: List of quenches when data were recorded (columns 5 and 7 indicates the data recorded by the 1^{st} oscilloscope, columns 9 and 11 those recorded by the 2^{nd} oscilloscope; the first column at the right of each signal shows the gain used for that signal).

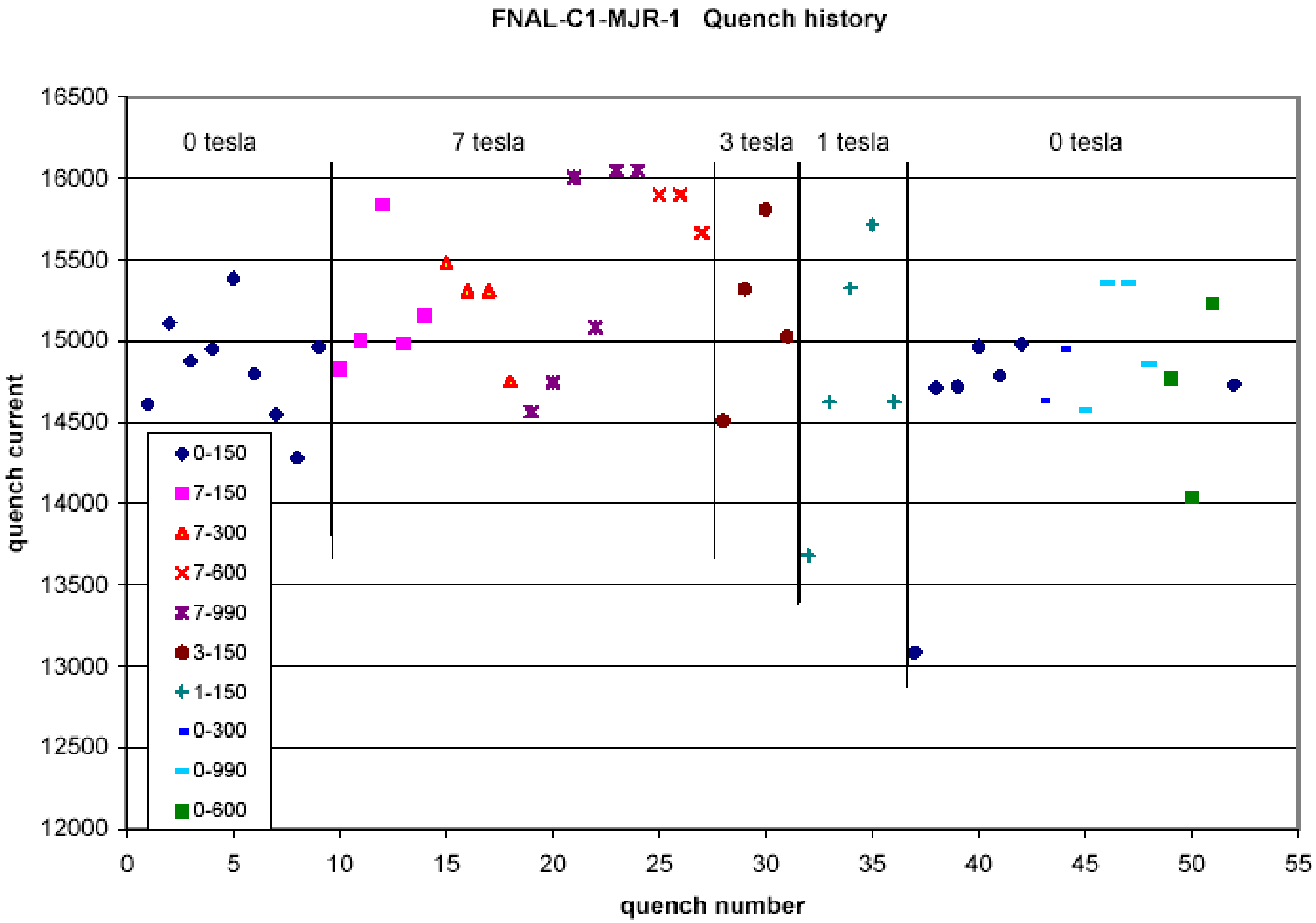

Figure 3: Quench history showing the quench current (A) at several background fields. The legend shows the background field (T) and the ramp rate (A/s) of each data set.

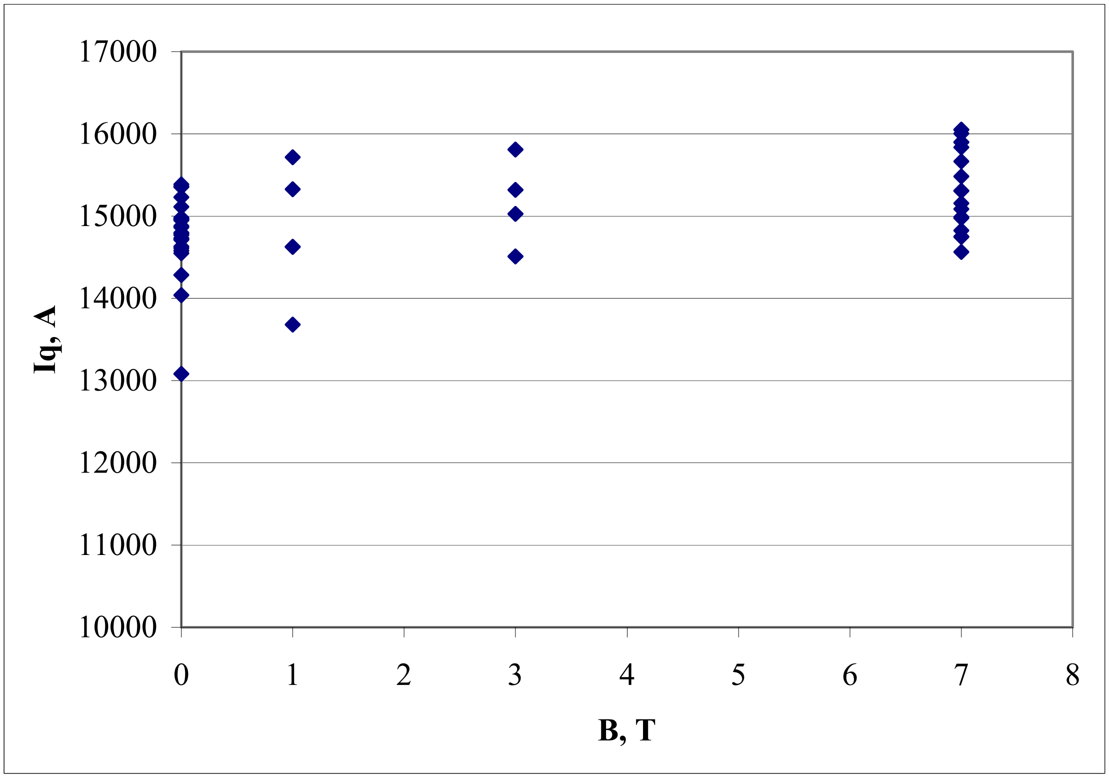

Figure 4: Quench current vs. background field.

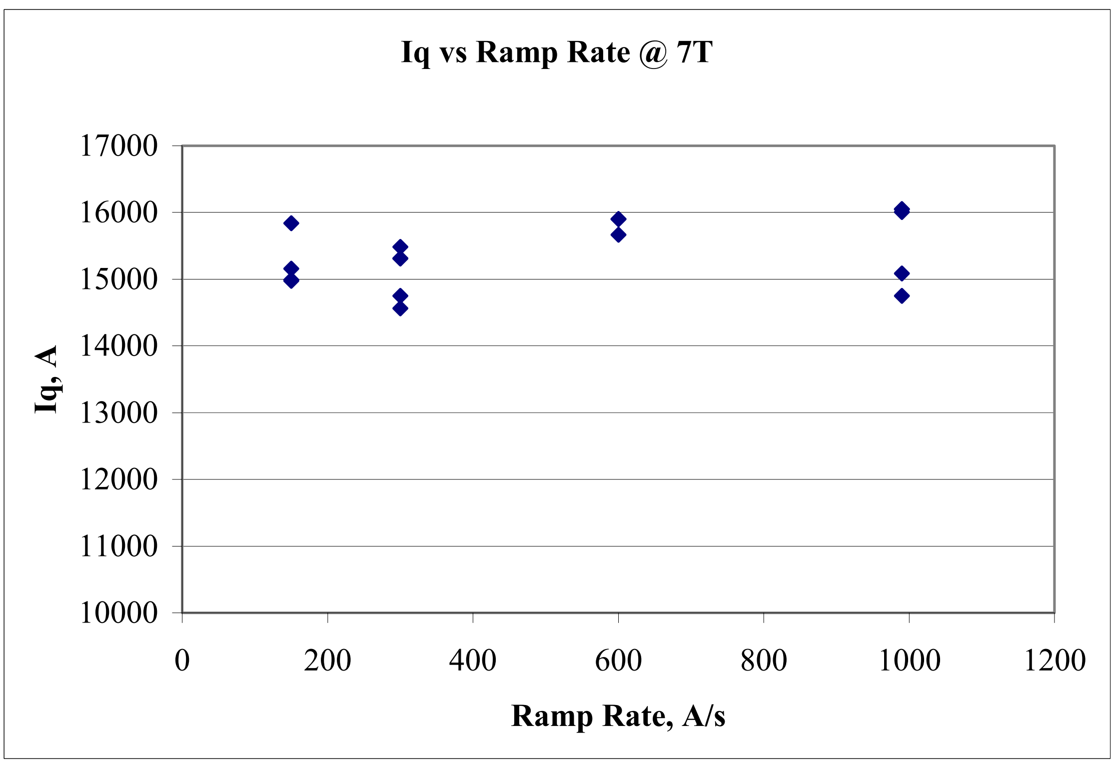

Figure 5:Quench current vs. ramp rate at 7 T background field.

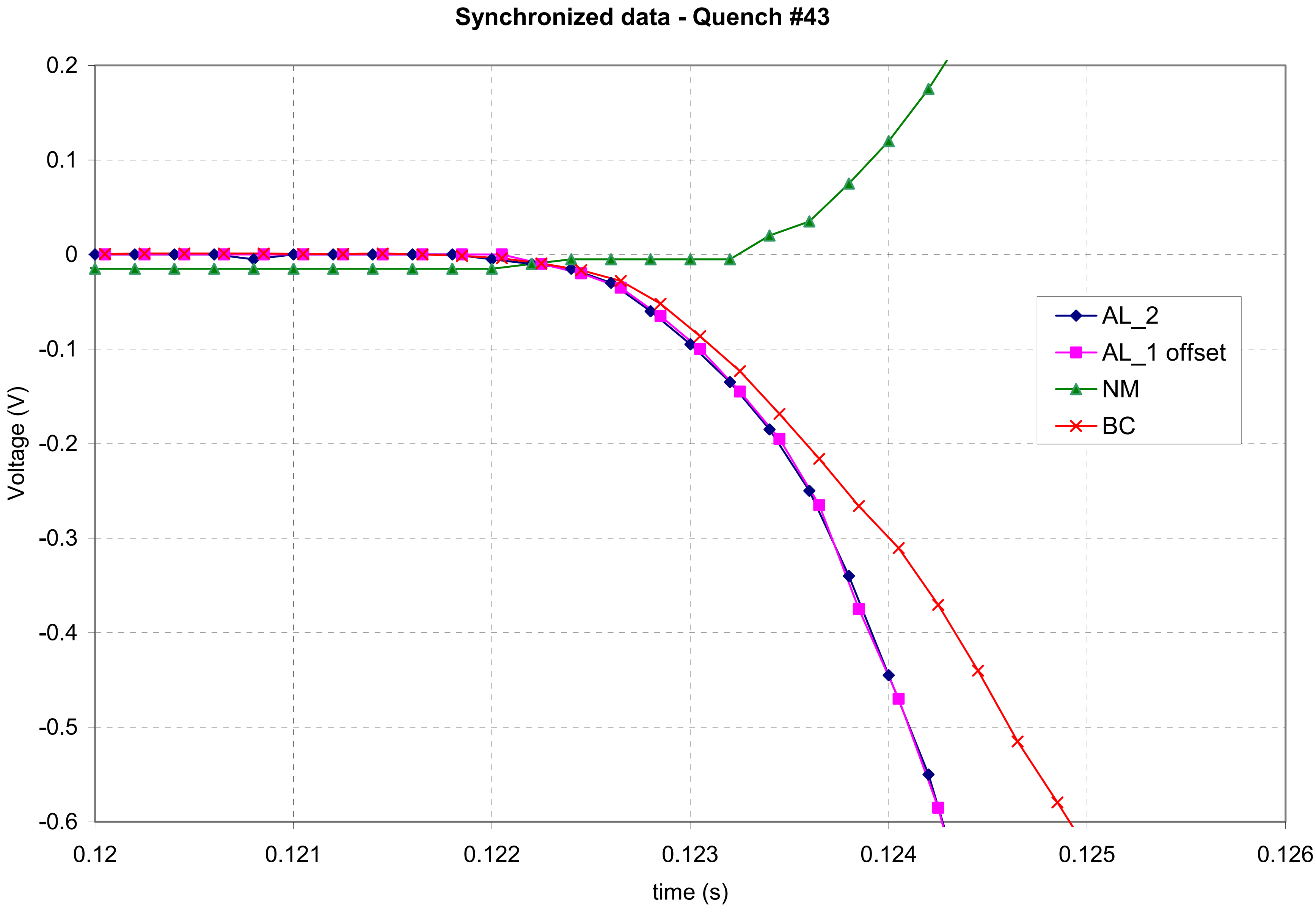

Figure 6: Voltage growth at the beginning of quench #43. For the legend see voltage tap schematic in Figure 2.

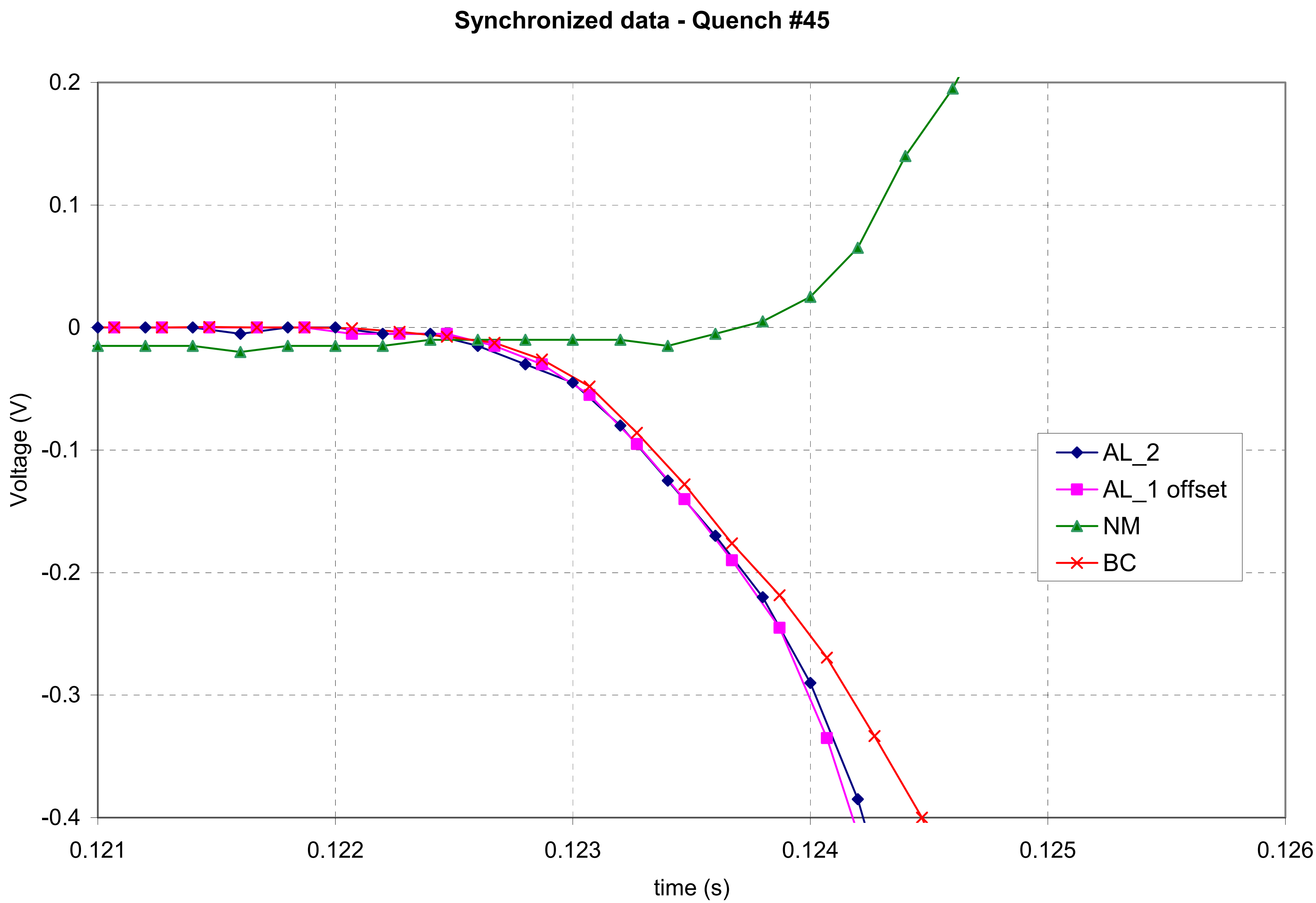

Figure 7: Voltage growth at the beginning of quench #45. For the legend see voltage tap schematic in Figure 2.

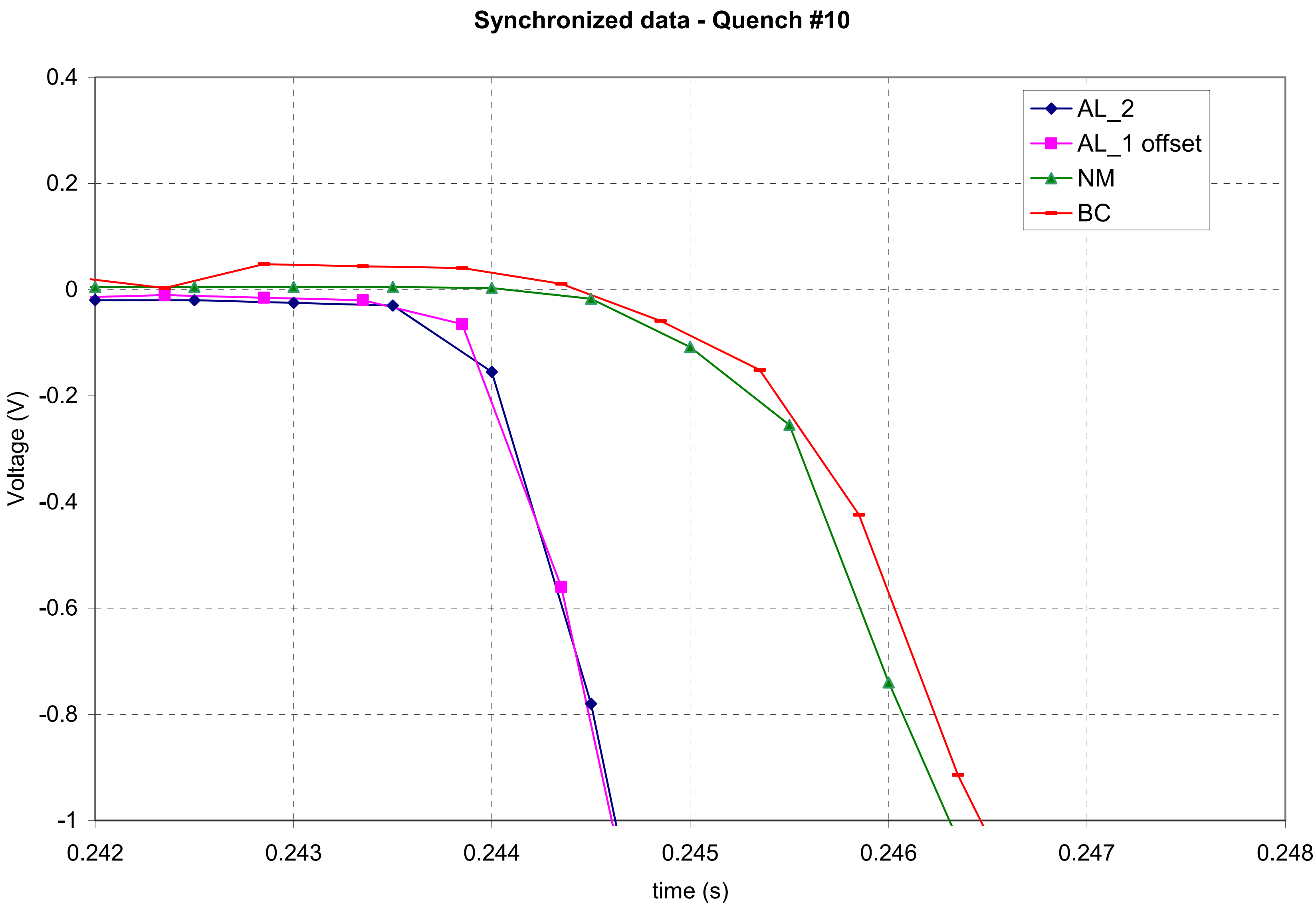

Figure 8: Voltage growth at the beginning of quench #10. For the legend see voltage tap schematic in Figure 2.